Displaced multileptons at the LHC-probing a 125 GeV new boson in the $\mu\nu$SSM

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The $\mu\nu$SSM provides a solution to the μ-problem of the minimal supersymmetric standard model and accounts for light neutrino masses by simply using right-handed neutrino superfields. As a consequence of this mechanism, R-parity is broken. We discuss possible signals of the $\mu\nu$SSM at the LHC, in view of the recent discovery by ATLAS and CMS experiments of a new particle compatible with the Standard Model Higgs boson. We show that the $\mu\nu$SSM will manifest itself in events with multileptons originating from displaced vertices.

The ATLAS [1] and CMS [2] experiments have recently observed a new boson with a mass around 125 GeV. In spite of the observed decay rates of this particle compatible with those of the Standard Model (SM) Higgs boson, a departure from the SM predictions remains a possibility since new LHC data are being analysed.

The 'μ from ν' Supersymmetric Standard Model ($\mu\nu$SSM) [3, 4], uses right-handed neutrino superfield(s) to generate light neutrino masses and to solve the μ-problem [5] of the Minimal Supersymmetric Standard Model (MSSM). The spectrum and the vacua of the $\mu\nu$SSM were studied in [4, 6], while its neutrino sector was discussed in detail in [6–8]. Neutralino decay rates and possible signals at colliders were analysed in [7–12]. In particular, in [12] the decays of the Higgses were analyzed and viable benchmark points for LHC searches were provided.

In this letter, we continue the latter analysis [12] placing special emphasis on a signal featuring non-prompt multileptons at the LHC, arising from the decay of a 125 GeV scalar into a pair of long-lived neutralinos. Such a signal would provide an unmistakable signature of the $\mu\nu$SSM through the new boson discovered by ATLAS and CMS.

The superpotential of the $\mu\nu$SSM is given by [3]:

$$W = \epsilon_{ab}(Y_{u_{ij}}\,\hat{H}_u^b\,\hat{Q}_i^a\,\hat{u}_j^c + Y_{d_{ij}}\,\hat{H}_d^a\,\hat{Q}_i^b\,\hat{d}_j^c + Y_{e_{ij}}\,\hat{H}_d^a\,\hat{L}_i^b\,\hat{e}_j^c$$
$$+ Y_{\nu_{ij}}\,\hat{H}_u^b\,\hat{L}_i^a\,\hat{\nu}_j^c - \lambda_i\,\hat{\nu}_i^c\,\hat{H}_d^a\hat{H}_u^b) + \frac{1}{3}\kappa_{ijk}\hat{\nu}_i^c\hat{\nu}_j^c\hat{\nu}_k^c \ , \ (1)$$

where $\hat{\nu}_i^c$ represents the i-th right-handed neutrino superfield, with $i, j, k = 1, 2, 3$ family indices, and $a, b = 1, 2$ are $SU(2)_L$ indices.

We work in the framework of supergravity, where in addition to the usual D and F terms the tree-level neutral scalar potential receives the soft-term contribution [3, 4]. Once the electroweak symmetry is spontaneously broken, the neutral scalars develop in general the following vacuum expectation values (VEVs): $\langle H_d^0\rangle = v_d$, $\langle H_u^0\rangle = v_u$, $\langle\tilde{\nu}_i\rangle = \nu_i$, $\langle\tilde{\nu}_i^c\rangle = \nu_i^c$.

As a consequence of R-parity breaking, all the neutral fermions (scalars) mix together. Neutralino

mass eigenstates are denoted by $\tilde{\chi}_{a'}^0$, with $a' = 1, ..., 10$, and in our convention $\tilde{\chi}_{1,2,3}^0$ are the ones dominated by the left-handed neutrinos and $\tilde{\chi}_4^0$ is what we call the lightest neutralino. Assuming CP-conservation, the eight CP-even (seven CP-odd) mass eigenstates are denoted by $h_\alpha(P_{\alpha'})$. We also assume that h_4 is the one dominated by the lightest doublet-like Higgs, while the three lightest scalars and pseudoscalars are composed mainly of right-handed sneutrinos.

We analyze in this letter a concrete benchmark point, inspired by the ones presented in [12], representing a quite general and interesting region of the parameter space. As in previous works (see e.g. [4]), we eliminate eight soft masses in favor of the corresponding VEVs. Here we also fix the VEVs of the right-handed neutrinos to be $\nu_i^c = \nu^c = 780$ GeV, $\tan\beta \approx \frac{v_u}{v_d} = 3.7$ and $v \approx \sqrt{v_u^2 + v_d^2} \approx 174$ GeV. We assume gaugino mass unification at the GUT scale, and consider $M_2 = 500$ GeV at low energy. In addition, we have fixed the following universal soft parameters: $m_{\tilde{e}^c} = m_{\tilde{u}^c} = m_{\tilde{d}^c} = m_{\tilde{Q}} = 1$ TeV, $A_\lambda = 990$ GeV, $A_\kappa = 5$ GeV, $A_e = A_d = -A_\nu = 1$ TeV and $A_u = 2.4$ TeV.

We stress that the chosen values of $m_{\tilde{Q}}$ and A_u are crucial to obtain a doublet-like Higgs of 125 GeV, since loop corrections are necessary to reach such a mass. Nevertheless, in contrast to the MSSM, the small mixing with the light right-handed sneutrinos also contributes to reach this value of 125 GeV. The values of A_λ and A_κ are chosen in such a way that the potential obtains a physical minimum with small pseudoscalar masses. The remaining soft parameters can be arbitrarily changed without altering significantly the discussion presented here.

The low-energy dimensionless free parameters that we assume are: $\lambda_i = \lambda = 0.11$, $\kappa_{111} = -7.3\times10^{-3}$, $\kappa_{222} = -7.5\times10^{-3}$, $\kappa_{333} = -7.7\times10^{-3}$, setting to zero all other κ_{ijk}. Considering that the three κ_{iii} parameters are nearly degenerate, set to a common value κ, only one linear combination of the right-handed neutrinos mix in an efficient way with

the MSSM neutralinos. Then, depending on the sign of κ, $\tilde{\chi}_4^0$ or $\tilde{\chi}_6^0$ will have a significant MSSM neutralino component. In our example, $m_{\tilde{\chi}_4^0} \approx 9.6\,\text{GeV}$, $m_{\tilde{\chi}_5^0} \approx 11.5\,\text{GeV}$ and $m_{\tilde{\chi}_6^0} \approx 11.9\,\text{GeV}$. We have chosen for this letter a negative κ, in such a way that the MSSM neutralino component of $\tilde{\chi}_4^0$ is significant producing $Br(h_4 \to \tilde{\chi}_4^0 \tilde{\chi}_4^0) \approx 6\%$. If a positive κ were selected, the h_4 decay would yield soft leptons, difficult to trigger due to their very low transverse momentum, p_T. These leptons would result from $h_4 \to \tilde{\chi}_6^0 \tilde{\chi}_6^0$, followed by decays such as $\tilde{\chi}_6^0 \to \tilde{\chi}_{4,5}^0\, \mu^+\mu^-$ and $\tilde{\chi}_5^0 \to \tilde{\chi}_4^0\, \mu^+\mu^-$.

In the situation we are interested in, the $\tilde{\chi}_4^0$ decays mainly to a pseudoscalar and a neutrino, with pseudoscalar masses $m_{P_1} \approx 3.6\,\text{GeV}$, $m_{P_2} \approx 3.8\,\text{GeV}$ and $m_{P_3} \approx 5.5\,\text{GeV}$. Although the P_i are in a good approximation on shell, we have nevertheless computed the three-body neutralino decays instead of the simplified two-body decays. The $\tilde{\chi}_4^0$ decays are dominated by $\tilde{\chi}_i^0 \tau^+\tau^-$, with $Br(\tilde{\chi}_4^0 \to \sum_{i=1}^3 \tilde{\chi}_i^0 \tau^+\tau^-) \approx 99\%$, with the remaining 1% shared between decays to a neutrino and a μ pair or a quark pair. The Higgs boson decay chain considered in our analysis is then $h_4 \to \tilde{\chi}_4^0 \tilde{\chi}_4^0 \to 2P_i^* 2\nu \to 2\tau^+ 2\tau^- 2\nu$.

The matrix $Y_{\nu_{ij}}$ and the VEV of the left-handed neutrinos, ν_i, are closely connected to the neutrino-sector predictions. The pseudoscalar decay, on the other hand, is, in very good approximation, independent of $Y_{\nu_{ij}}$ (and ν_i). Hence the neutralino decay branching fractions to leptons (through the pseudoscalar decay) are independent of these parameters. As a consequence, a range of $Y_{\nu_{ij}}$ and ν_i values can be chosen, predicting neutrino mixing angles and mass differences consistent with experimentally measured values [13], providing at the same time a multilepton event topology with displaced vertices.

For our benchmark point we have fixed the neutrino-sector parameters in order to obtain the mass of the third neutrino, $\tilde{\chi}_3^0$, around $4.9 \times 10^{-11}\,\text{GeV}$, thus obtaining a decay width $\Gamma_{\tilde{\chi}_4^0} \approx 6.7 \times 10^{-16}\,\text{GeV}^{-1}$, corresponding to a proper lifetime $\tau_{\tilde{\chi}_4^0} \approx 10^{-9}$ s. But we can increase the absolute neutrino mass scale so as to obtain shorter proper lifetimes. Another possibility to vary the neutralino lifetime is its composition. Varying the values of the gaugino masses, the effective Majorana mass, $2\kappa\nu^c$, or the effective μ-parameter, $\mu_{\text{eff}} = 3\lambda\nu^c$, we can change the Higgsino and gaugino composition of the neutralino, making it possible to obtain different decay lengths.

We have confirmed that variations on the benchmark point do not induce significant changes in the lepton multiplicity, but they do affect neutralino lifetimes, i.e. decay lengths, which remain in the experimental accessible range of mm to m. Essential to the robustness of the displaced multilepton signature is the fact that in this model neutrino-physics experimental constraints can be easily respected at tree level [6, 7, 9].

Before describing the expected signals at the LHC, we briefly discuss the tools used in our analysis. The event generator PYTHIA (v. 6.4.09) [14] has been used with default parton distribution function. The renormalisation/factorisation scale was set equal to the parton-level center-of-mass energy of 8 TeV. The initial and final state radiation (ISR, FSR) with multiple interactions were activated during the generation of 10^6 proton-proton collisions. The mass spectrum and decays are computed with a custom-developed code. For the Higgs gluon fusion cross section, the SM Higgs [15] is (equal to 6.51 pb) rescaled by the reduced coupling [12], yielding a next-to-next leading order $gg \to h_4$ production cross-section of 19.3 pb. The distributions that follow have been normalised to an integrated luminosity of $\mathcal{L} = 20$ fb^{-1}, corresponding to the full 2012 dataset expected to be recorded by ATLAS and CMS at $\sqrt{s} = 8$ TeV. Finally, the PYTHIA-generated hard-scattering events are passed through the package PGS4 [16], in order to simulate the detector response.

The $\mu\nu$SSM is characterised by the production of several high-p_T leptons, as demonstrated in Fig. 1 (top), where the electron, muon and hadronically decaying tau multiplicity distributions are drawn for leptons with $p_T > 10$ GeV. As a consequence of the dominant decay chain mentioned earlier, the tau multiplicity is considerable even though the τ-identification efficiency is much lower ($\sim 50\%$) when compared with that of electrons and muons ($\gtrsim 95\%$). Occasionally highly collimated QCD jets fake hadronically decaying τ's and, as a result, τ multiplicity exceeds the expected number of four taus. Electrons and muons, on the other hand, are produced in the leptonic decays of taus; in addition muons occur in pseudoscalar decays to muon pairs. High tau multiplicity of course disappears with a higher p_T cut.

The distributions of the transverse momentum of the leading and of the 3rd leading lepton are shown in the bottom row of Fig. 1. It is evident that the leading lepton is energetic enough to trigger the event, should a single-lepton trigger is deployed. The rest of the leptons have sufficient p_T to be selected by a multilepton-based analysis, such as the ones developed by CMS [17] and ATLAS [18]. For instance, for the third leading e, μ, and hadronically decaying τ, around 0.05, 10 and 43 events with $p_T > 10$ GeV are expected, respectively. Clearly, multi-electron signature is least promising.

Such analyses, apart from the requirement of at least three or four leptons (including taus), require a high value of E_T^{miss} or of the scalar sum of reconstructed objects: leptons, jets and/or E_T^{miss}. In the case of the $\mu\nu$SSM, the neutrinos produced in the $\tilde{\chi}_4^0$ decays are expected to give rise to moderately high missing transverse energy, E_T^{miss}, as depicted in Fig. 2 (left). Besides E_T^{miss}, the scalar sum of the p_T
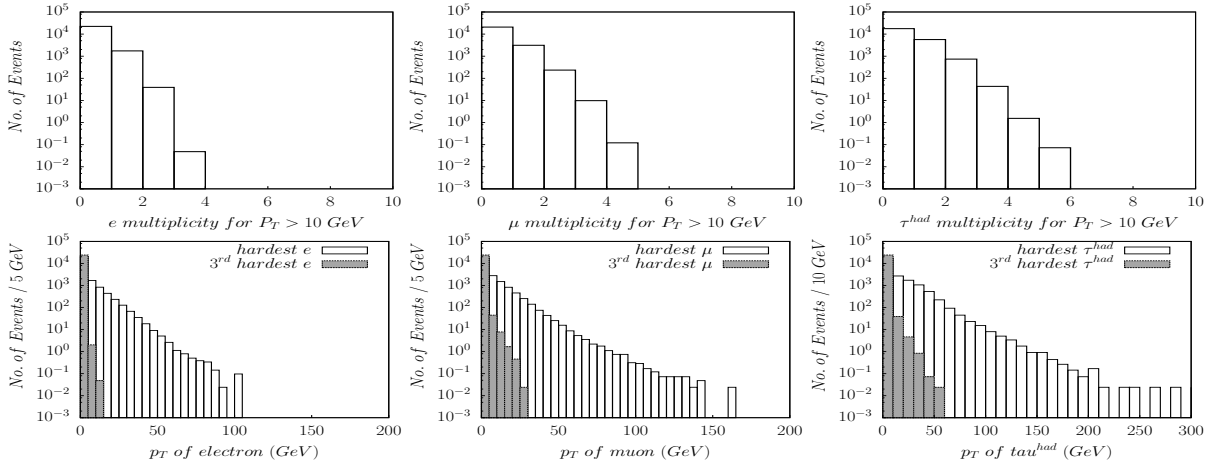
FIG. 1: Multiplicity (top row) for e (left), μ (middle) and hadronically decaying τ (right) with $p_{\mathrm{T}} > 10$ GeV. p_{T} distributions (bottom row) for the leading (white) and the 3rd leading (light grey) e (left), μ (middle) and hadronically decaying τ (right). These plots correspond to $\sqrt{s} = 8$ TeV with $\mathcal{L} = 20$ fb^{-1}.

of all reconstructed leptons, H_{T}^{ℓ}, is also high in such events, as shown in Fig. 2 (right). Alternatively, the sum of $E_{\mathrm{T}}^{\mathrm{miss}}$ and H_{T}^{ℓ} can be deployed to further reject the background from SM processes. These observables can provide additional handles when selecting events with many leptons.

Furthermore, the invariant mass, $m_{\ell\ell}$, of two same-flavour opposite-charge leptons may be used to suppress SM background coming from $Z + X$ events with $Z \to \ell^{+}\ell^{-}$, by selecting events outside the Z-mass window, i.e. $|m_{\ell\ell} - m_{Z}| > w$, where w is the chosen window half width. Should a possible excess of four-lepton events is observed at LHC, the question of how to distinguish a $\mu\nu$SSM from a Next-to-MSSM (NMSSM) [19] arises. In that case, the two or four-lepton invariant mass distribution for the NMSSM would have a very sharp peak at the relevant Higgs mass, whereas the $\mu\nu$SSM could have a broader one due to the neutrino associated decay mode together with displaced vertices.

A word of caution is due here. In the discussion on multilepton analyses so far, *prompt* leptons are selected after imposing an upper limit on the transverse and the longitudinal impact parameters, in order to reject cosmic-ray muons and insure good-quality track selection. Such a selection criterion should be relaxed or even reversed, if sensitivity to the $\mu\nu$SSM events is sought after. The reason stems from the long lifetime of the $\tilde{\chi}_4^0$ and hence the displaced vertex that its decay creates. This feature is quantified in the middle plot of Fig. 2, were the decay-length distribution is drawn. As expected from the proper decay length of $c\tau_{\tilde{\chi}_4^0} \approx 30$ cm, in a significant percentage of events, $\tilde{\chi}_4^0$ decays inside the tracker, e.g. 28% of events decay within 30 cm and 44% events within 1 m. Therefore, the $\mu\nu$SSM signal events will be characterised by displaced τ-leptons plus neutrinos. This distinctive signature opens up the possibility to exploit current or future variations

of analyses carried out by ATLAS and CMS looking for a displaced muon and tracks [20] or searching for displaced dileptons [21] or muon jets [22] arising in Higgs decays to pairs of long-lived invisible particles.

The kinematics of the displaced vertices and their products are demonstrated in Fig. 3. The $\tilde{\chi}_4^0$ boost, expressed by $\beta\gamma$, where β is $\tilde{\chi}_4^0$ velocity over c and γ the Lorentz factor, versus the pseudorapidity η is shown on the left. The shape reflects the fact that a single particle (h_4) is produced at the hard scattering of pp collisions, hence low momentum is expected in the central region. The average boost is comparable to the signal analysed in an ATLAS search for a muon and tracks originating from displaced vertices (DV) [20]. The boost affects the efficiency with which such a DV can be reconstructed, since high $\tilde{\chi}_4^0$ boost leads to collimated tracks difficult to differentiate from primary vertices.

In the middle plot in Fig. 3, the spacial distribution of a DV is displayed in cylindrical coordinates. A large fraction of DVs falls in the inner-tracker volume of an LHC experiment, i.e. $\rho_{\mathrm{DV}} \lesssim 1$ m and $|z_{\mathrm{DV}}| \lesssim 2.5$ m, thus DVs arising in the $\mu\nu$SSM should be detectable at LHC, either with existing analyses [20–22] or via variations of those to search for displaced taus and $E_{\mathrm{T}}^{\mathrm{miss}}$.

Last, in the right panel of Fig. 3, we show the correlation between the number of charged tracks in each DV, N_{trk}, and the their invariant mass, m_{DV}. A selection of high-N_{trk} and high-m_{DV}, among other selection criteria, has been demonstrated [20] to efficiently suppress background from long-lived SM particles (B-mesons, kaons). The modulation observed in N_{trk} is due to the one-prong or three-prong hadronic τ decays.

To summarize, the production of a Higgs boson with a mass of 125 GeV in the context of the $\mu\nu$SSM at the LHC is characterised by two significantly displaced vertices due to the long lifetime of the $\tilde{\chi}_4^0$.
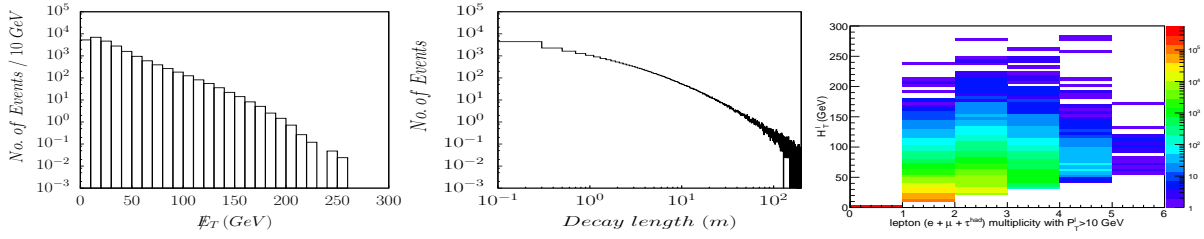
FIG. 2: $\not{E}_T$ distribution (left), $\tilde{\chi}_4^0$ decay-length distribution (middle) and $H_{\rm T}^\ell$ versus lepton multiplicity (right) for $\sqrt{s} = 8\,{\rm TeV}$ and $\mathcal{L} = 20\,{\rm fb}^{-1}$.
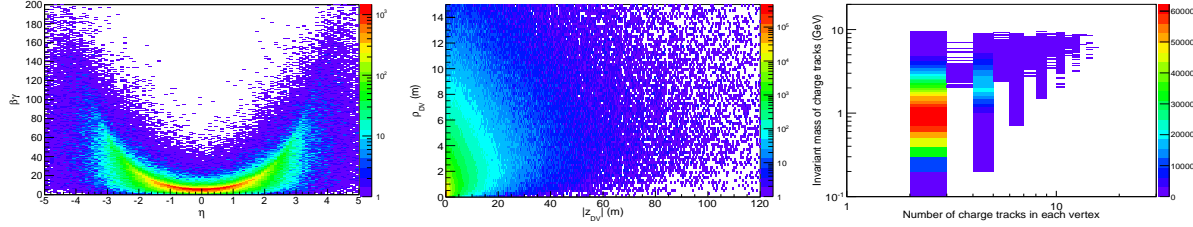

FIG. 3: $\beta\gamma$ versus η (left), $\rho_{\rm DV}$ versus $|z_{\rm DV}|$ (middle) and charged-track mass versus the number of charge particles in each vertex (right) for $\tilde{\chi}_4^0$ and for $\sqrt{s} = 8\,{\rm TeV}$ and $\mathcal{L} = 20\,{\rm fb}^{-1}$.

Such events could be probed by ATLAS and CMS with the currently available 8 TeV data in two ways: By looking for multilepton events when relaxing or even reversing the requirement for the leptons to come from the primary vertex, and by adapting existing searches for displaced vertices to be sensitive to displaced taus. In either case, a moderately high missing transverse energy due to neutrinos is expected.

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